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Cover: *Antenna-transceiver unit slung under Hughes 500 helicopter for radar profilometry of test area. (Photograph by Arnold Dean.)*

CRREL Report 77-8

Remote sensing of accumulated frazil and brash ice in the St. Lawrence River

Arnold M. Dean, Jr.

April 1977

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A broadbanded impulse radar system was used for aerial detection of accumulated frazil and brash ice in a 9.5-km reach of the St. Lawrence River near Ogden Island. The remote sensing and data reduction system developed for the project provided data sufficient for production of a contour map having 1-ft intervals. With this contour map, the accumulation pattern of frazil and brash ice could be analyzed. Recommendations are given for improving the performance of the aerial profiling system.

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PREFACE

This report was prepared by Arnold M. Dean, Jr., Electrical Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The research was primarily funded by Corps of Engineers Civil Works Project 31350, *Formational Processes of Frazil Ice.* Partial funding was provided by the St. Lawrence Seaway Development Corporation under Interagency Agreement No. 23182.

Dr. George Ashton, Austin Kovacs and James Wuebben technically reviewed the manuscript.

The author wishes to express his thanks to Austin Kovacs, CRREL, for suggesting the evaluation of the Geophysical Survey Systems, Inc. (GSSI) equipment; to Bob Conner, Power Authority of the State of New York, John Adams, St. Lawrence Seaway Development Corporation (SLSDC), John Keon, Ontario Hydro, and Tom Wigle, Ontario Hydro, for cooperation in the investigation by making equipment and field personnel available; to Sandy Ross, Ontario Hydro, who ably piloted the data collection helicopter; to John Kelly, Ed Hollander and Cy Mills, SLSDC, and John Ho, Ontario Hydro, Jim Lasota, CRREL, and Tom Fenwick, GSSI, for untiring and competent field assistance; to Dr. Rex Morey, GSSI, for field assistance and computer processing of the data; to Bill McGovern, SLSDC, and Bill Crooke, Ontario Hydro, for the availability of their ground truth data and equipment; to Captain Robert Papelian, U.S. Customs, for his personal assistance; and to Carl Martinson, CRREL, for many hours spent in data reduction.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
foot	0.3048*	meter
knot	0.5144444	meter/second
$foot^3$/second	0.02831685	$meter^3$/second

*Exact

REMOTE SENSING OF ACCUMULATED FRAZIL AND BRASH ICE IN THE ST. LAWRENCE RIVER

by

Arnold M. Dean, Jr.

BACKGROUND

The work described in this report was performed in the Ogden Island area of the International Rapids of the St. Lawrence River. This area extends some 9.5 km from Pinetree Point (just below Iroquois, Ontario, Canada) to the Murphy Islands (at Morrisburg, Ontario). The formation and control of the ice cover in this reach have presented problems to power generation since the construction of the facilities of the St. Lawrence Power Project.[3] The consideration of extended or year-round operation of the St. Lawrence Seaway has also brought the Ogden Island area to the attention of navigation officials.[4]

Controlling the generation and accumulation of frazil and brash ice in this reach is the ultimate goal of those concerned, as this affects both navigation and power generation. To accomplish this goal an initial ice cover must be formed as quickly as possible, and those characteristics which enhance subsurface ice accumulation must be identified and minimized. The formation of an ice cover is particularly important since it greatly reduces the potential for ice production from an open reach in the St. Lawrence River. Depending upon the weather conditions of the season, heat budget calculations indicate that for every areal unit of surface left uncovered through the winter, between 10 and 25 cubic units of ice will be formed. Field measurements have shown that the porosity of accumulated frazil is 40-50%. Hence the volume occupied by frazil is about twice the volume of ice produced, or accumulated frazil could be between 17 and 50 volumetric units per unit of open surface area.

The economics of ice control are significant, since 1 ft of lost head at the dam is equivalent to over 250 MWh of energy lost per day. The head loss due to frazil and brash ice attached beneath the cover in the Ogden Island area may vary between 1 and 4 ft throughout the majority of the winter, in addition to the normal loss caused by the ice cover. Although the reach composes only 14% of the river length from Ogdenburg to the Long Sault Dam, some 33% to 58% of the total head differential was lost in the study area during the 1975-76 season. This appears to be typical.

Consequently, the formation of the ice cover in this area requires careful control of the flow through the dam. Variable weather conditions, high water velocities and large frazil generation combine to make this a formidable task. During and after formation, frazil and underturned brash ice become attached to the underside of the ice cover. Field data indicate that this accumulation causes a typical 20-30% constriction in the cross section of the channels around Ogden Island. To alleviate the resulting head loss at the downstream power plant, operations personnel increase the flow through the dam during warm periods in an attempt to reduce the attached ice. Careful control must be exercised, since an excessive increase in the flow changes the slope of the water in the forebay and may collapse the ice cover. Conversely, large amounts of frazil, if left in place, may enhance jamming during breakup. The controller needs to know the configuration and amount of ice in the forebay in order to weigh these alternatives.

Navigation through such great amounts of ice will be impeded and channel maintenance can become unsafe. Tug boat operators on the Illinois River have reported that the accumulation of frazil and brash ice in the channel has increased resistance to the point where little or no forward progress could be made at full power.[1,2] Icebreaking tugs on the St. Lawrence River at Beauharnois, Quebec, have been nearly capsized by a surfacing frazil mass attached to sheet ice broken away from the edge of the channel.[7]

In order to deal quantitatively with these ice problems, basic data must be obtained, ice accumulation patterns defined, and the characteristics of accumulation

investigated. It also is important to determine the river's flow regime, since there appears to be a limiting velocity above which frazil cannot attach. Further, some flow patterns tend to enhance the accumulation of frazil under the ice sheet while others tend to entrain the ice.

Manual sounding has been the only method that has previously been available to accomplish a widespread mapping of ice accumulation as required in the study area. During this past year a radar ice thickness profilometer, developed by Geophysical Survey Systems, Inc., was tested by CRREL under various circumstances to determine applicability for frazil ice detection and ice thickness measurements in fresh water. The results of the field work were encouraging. Such an instrument used in a remote sensing role was shown to be a definite advantage for investigating a large or relatively inaccessible area.

OBJECTIVES

The objectives of this work were as follows:

1. To produce a contour map of frazil ice accumulation in the International Rapids of the St. Lawrence River from Pinetree Point to the Murphy Islands.
2. To evaluate the radar system as a remote sensing system for the detection of frazil ice accumulation.
3. To analyze the accumulation pattern of the frazil ice.

PROFILING SYSTEM

The radar profilometer combines, in a broadbanded pulse, frequencies which have the capability of penetration through water and frequencies which give good resolution. In single-frequency systems, these are opposing characteristics; i.e. systems with good resolution cannot penetrate a wet surface, and systems that can see through water cannot resolve less than a meter or so. While the system is still in a developmental stage for this application, the profiler is commercially available. Its radiated average power output of 5 mW is centered at 100 MHz with a 3-db band width of 100 MHz. The antenna is pulsed at a rate of 50 kHz and has a pulse width of 3 ns. The manufacturer of the profiler, Geophysical Survey Systems, Inc., prefers to quote a performance figure which is the ratio of the minimum detectable signal to the peak voltage out of the transmitter. This is stated to be 100 db for the utility antenna used in this study.[5]

The equipment functions as an echo sounding system using electromagnetic pulses and is able to detect and measure the depth of reflecting discontinuities to within a few centimeters, depending upon the electromagnetic parameters of the medium being probed. The system can be considered as the electromagnetic equivalent of marine sonar. Real-time profile data may be displayed graphically on a stripchart recorder and/or recorded on magnetic tape for subsequent processing and playback. The echo or reflection from the air/ice, ice/frazil and ice/water interfaces is recorded, and the travel time to the surfaces is measured. Once the velocity of propagation within the ice is known, either from a knowledge of the electrical properties or from direct mechanical calibration by measurement of ice thickness, the travel time can be converted directly to layer thicknesses.[6]

The system is composed of a control unit, an antenna-transceiver unit, a graphic recorder and a magnetic tape recorder. Figure 1 shows the control unit and the magnetic tape recorder. The control unit is housed in a cubic metal case approximately 30 cm on a side, and contains all the control electronics, including the low-frequency signal processing circuits, control dials and a monitor oscilloscope. Weighing about 13 kg, the control unit is powered by a 12-V battery and draws about 1.5 A. The magnetic tape recorder stores the returned signal on frequency-modulated (FM) tape. Figure 2 shows the antenna-transceiver unit. This unit is rugged, weighs about 32 kg, and contains an antenna for transmission and reception, a transmitter, and the high-frequency components of the receiver. Thus, the cable connecting the antenna to the control unit carries only audio signals which are less susceptible to degradation. The graphic recorder, which is shown in Figure 3, weighs about 31 kg, and is an intensity-modulated recorder using multi-layered paper.[6]

During the past winter CRREL has made extensive use of the profiler system for ground monitoring of frazil accumulation. The work in the Ogden Island area marks the first time that the system was used to monitor frazil accumulation remotely.

APPROACH

Data were collected in the study area by three methods: airborne radar profiling, surface radar profiling and manual sounding. Both radar profiling and manual soundings were accomplished during the period 18-23 February 1976, and manual soundings were also taken during 10-13 February, 1 March, 11 March and 18 March 1976.

The airborne data collection configuration can be seen in the sketch of Figure 4. The data are sensed and

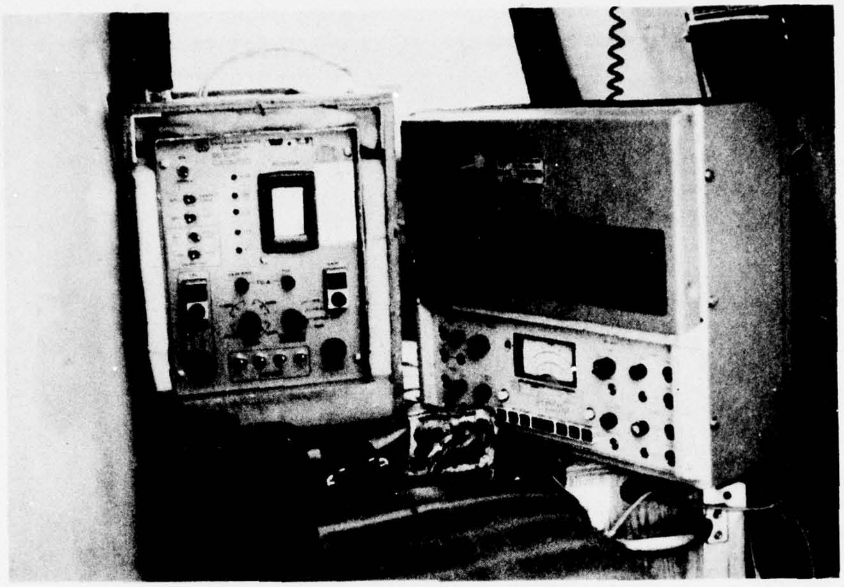

Figure 1. Profiler system's control unit (left) and magnetic tape recorder.

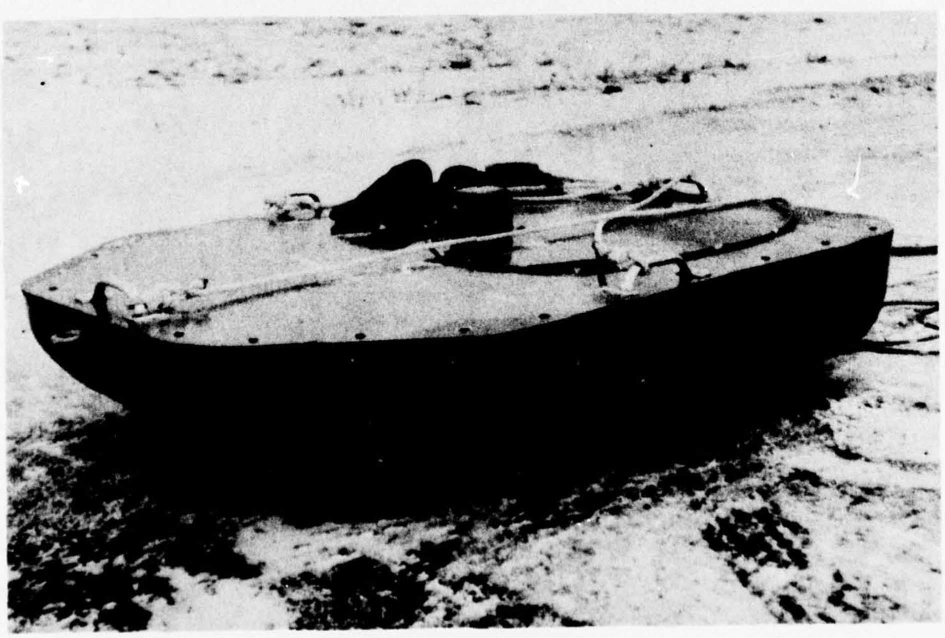

Figure 2. Antenna-transceiver unit of the profiler system.

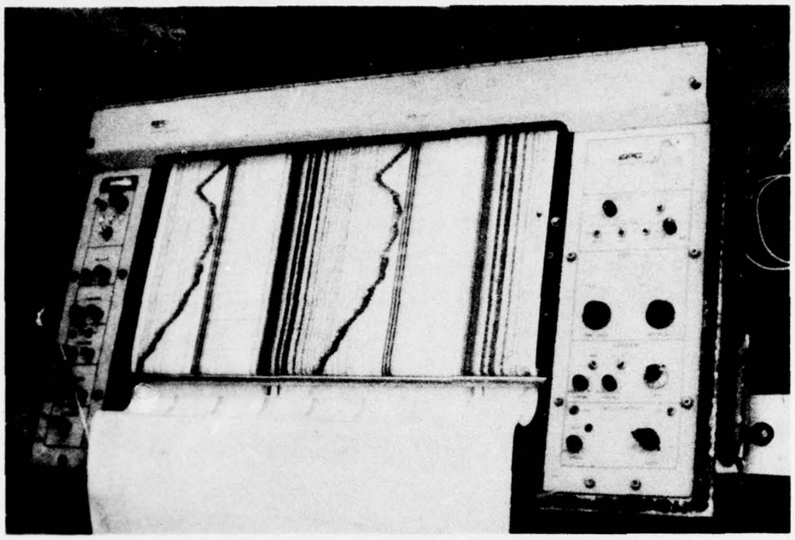

Figure 3. Graphic recorder used in the profiler system.

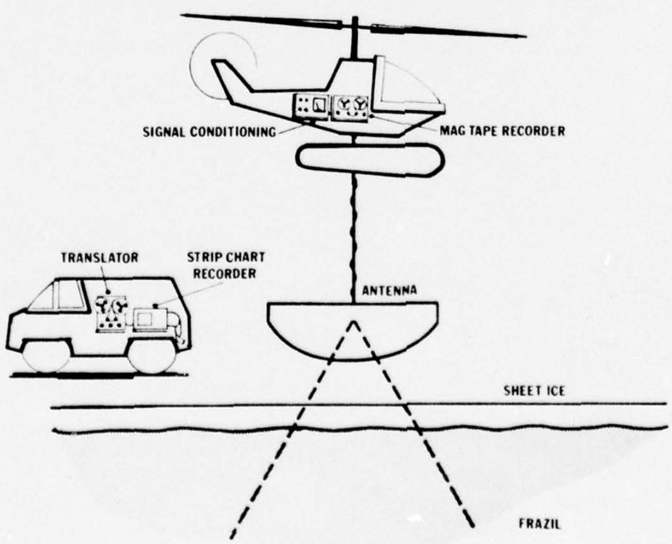

Figure 4. Remote data collection configuration of the profiler system.

recorded on magnetic tape from the helicopter and later transferred from the magnetic tape to the graphic recorder in a vehicle on the bank.

Longitudinal flight patterns were followed for both the north and south channels around Ogden Island, as shown in Figure 5. Each channel had a center flight approximately along its thalweg. The remaining four flight lines divided the channel equally between banks. These sets of lines tended to parallel each other above and below the island. Ten lines of flight traversing the channel above and below Ogden Island were planned. Because of inclement weather only the eight shown in Figure 5 were flown. These flight lines are lettered A-A, B-B, etc.

The numbered traverse lines on Figure 5 are registration lines that were located along the flight path to ensure proper longitudinal registration of the radar data. The registration lines were identified during flight by the alignment of prominent terrain or man-made features. To minimize flight speed variations due to wind, etc., and to facilitate the identification of benchmarks for registration lines, the direction of flight for a channel was the same; i.e. all data were taken going downstream in the north channel and all data were taken going upstream in the south channel.

The equipment shown in Figure 1 was carried in the Hughes 500 helicopter during airbone data collection. A 12-V automobile battery supplied the power for the equipment. The antenna-transceiver unit was slung some 10 m below the helicopter with a 4-point nylon rope suspension connected to the cargo hook of the helicopter (see cover photograph). The signal and power cable connecting the antenna-transceiver with the control unit was taped to one of the ropes and had a nonlocking connector at about the same level as the cargo hook. The remainder of the cable then went into the aircraft via a window port. The nonlocking connector was reinforced with a wrapping of solder.

This arrangement gave the connector adequate mechanical stability while still allowing the pilot to drop the antenna-transceiver in case of an emergency.

The antenna weight proved sufficient for stable operation and data collection at flight speeds of 40 to 60 knots. The front of the antenna was oriented with the front of the helicopter, and at data collection speeds of about 40 knots the orientation stayed true. This speed was selected as a compromise between slower speeds for more accurate data collection and higher speeds for vertical stability of the aircraft.

Profiling method

Data collection from a helicopter required a pilot and two other personnel. The pilot maintained the flight line, airspeed and approximate altitude. The second individual operated the radar set and tape recorder, kept a tape log (the location of particular data on the tape), and guided the pilot with fine altitude adjustments. The third individual located registration lines, entered benchmark data into the collected data by means of a pushbutton, and started and stopped the data collection.

Portions of the data were printed out on the ground-based graphic recorder during airborne data collection to ensure equipment operation, calibration, etc.; this was done after the completion of a tape. The entire tape was not immediately transferred since the graphic recorder operated at a much slower speed than the magnetic tape recorder. Data collection with the magnetic tape recorder along flight lines took only as long as the flight time, and there would necessarily have been a bottleneck at the printout if the entire tape had been printed during the data collection time. Spot checks appeared to provide adequate indicators of the quality of the data. This type of check was possible since the tape log allowed one to select particular portions of the data for review.

Surface radar profiling, conducted in this study mainly to compare the airborne and surface data, was accomplished by pulling the antenna-transceiver behind an airboat or by pulling the antenna-transceiver by hand for short distances. When the airboat method was used, the radar set and the magnetic tape recorder were placed in the airboat in an insulated box. Runs were limited by the length of the extended cable, in this case, 60 m. Hand towing was used to obtain a much slower and more controlled antenna-transceiver movement. Spot (nonmoving) measurements are not interpretable with the system, since there are various reflecting media within the ice itself. With a moving record, one can differentiate between reflections from local discontinuities and those from surfaces.

The procedure used for manual sounding in this study involved drilling through the surface ice and then penetrating the frazil or slush ice beneath to determine its thickness. There were two methods used to determine the frazil thickness. One method employed a rod to push down through the frazil and to feel the current below. The other method used a heavy, pointed plate that hammers down through the frazil, and then is turned flat and pulled back up to the bottom of the frazil. The two methods are compared in Table I.

Data reduction and interpretation

Figure 6 is a flow chart of the data reduction and interpretation procedure. Initially the data are collected, stored and associated with some location, and are then

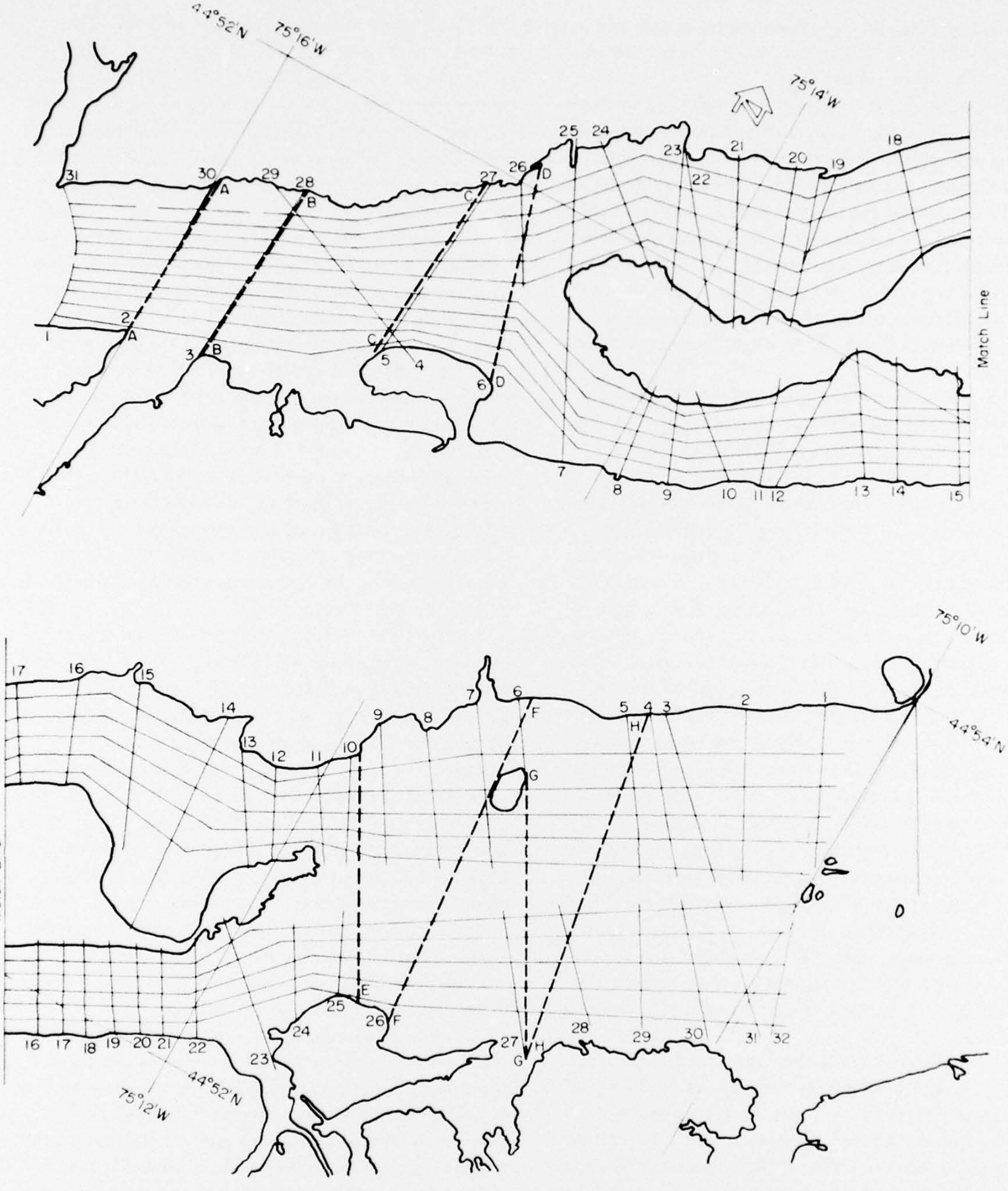

Figure 5. Registration lines (1-32) and flight lines (longitudinal) over the study area.

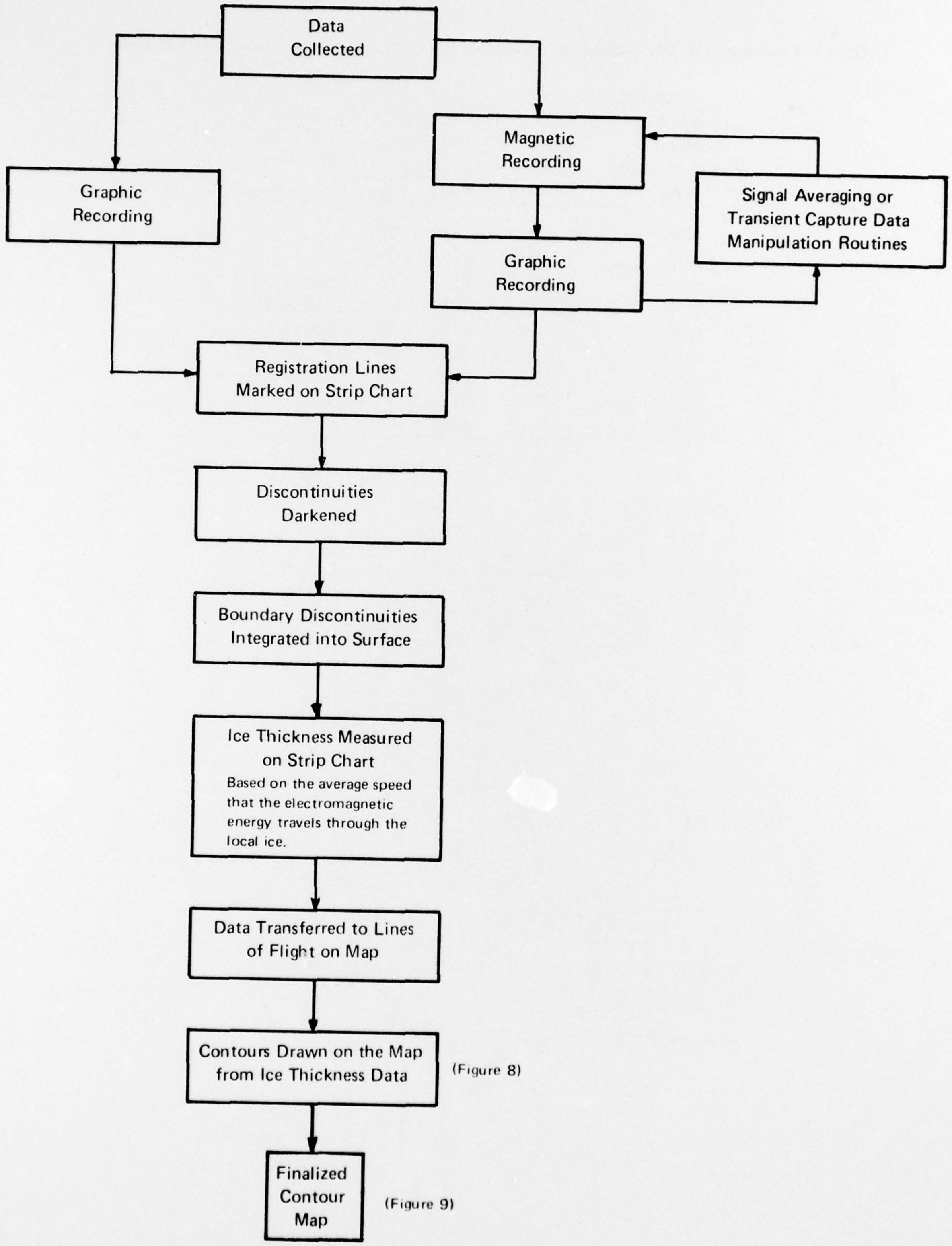

Figure 6. Data reduction and interpretation procedure.

Table I. Comparison of two methods of manual ice thickness measurement along a test section.

Test location (proceeding upstream – relative distances in ft)	*Surface ice thickness (in.)*	*Total ice thickness (in.)*		*Comments*
		Rod	*Plate*	
0-00	20	118	70	
0-10	18	118	75	
0-20	18	118	78	Significant
0-30	16-18	125	93	underturned
0-40	15-18	118	75	sheet ice
0-50	18	118	78	encountered
0-60	17	121	87	within the
0-70	17	118	80	frazil
0-80	15	120	85	

Figure 7. Ice thickness data transferred to the flight lines.

Figure 8. Contours drawn on the map from the ice thickness data.

printed out on the graphic recorder for inspection of the signal strength and noise level. The data are then modified by a signal averaging noise reduction routine, a computer program which reduces continuous (reflection) noise in the data. Further modification is accomplished by the transient capture routine, a computer program suggested by CRREL to alleviate the vertical deviations associated with the vertical instability of the aircraft (this program was not available at the time the data from this work were reduced). The registration lines are then indicated on the strip chart and parallel flight lines are posted together for comparison. Discontinuities are outlined so that the interfaces can be recognized more easily. The distances between the registration lines on the strip charts are divided into convenient increments for transferring ice thickness data to the map, where this same reference system has been employed (Fig. 5). The intervals marked between the registration lines on the strip charts are located on the map, and the ice thickness is then transferred from the strip charts at these intervals to the flight lines on the map. (A portion of the map at this point in the data reduction is shown in Figure 7.) Contours are then drawn from the data points on the map as shown in Figure 8. It was found that the work on the map was more conveniently performed on an enlarged copy because of the congestion. The final contour map is shown in Figure 9.

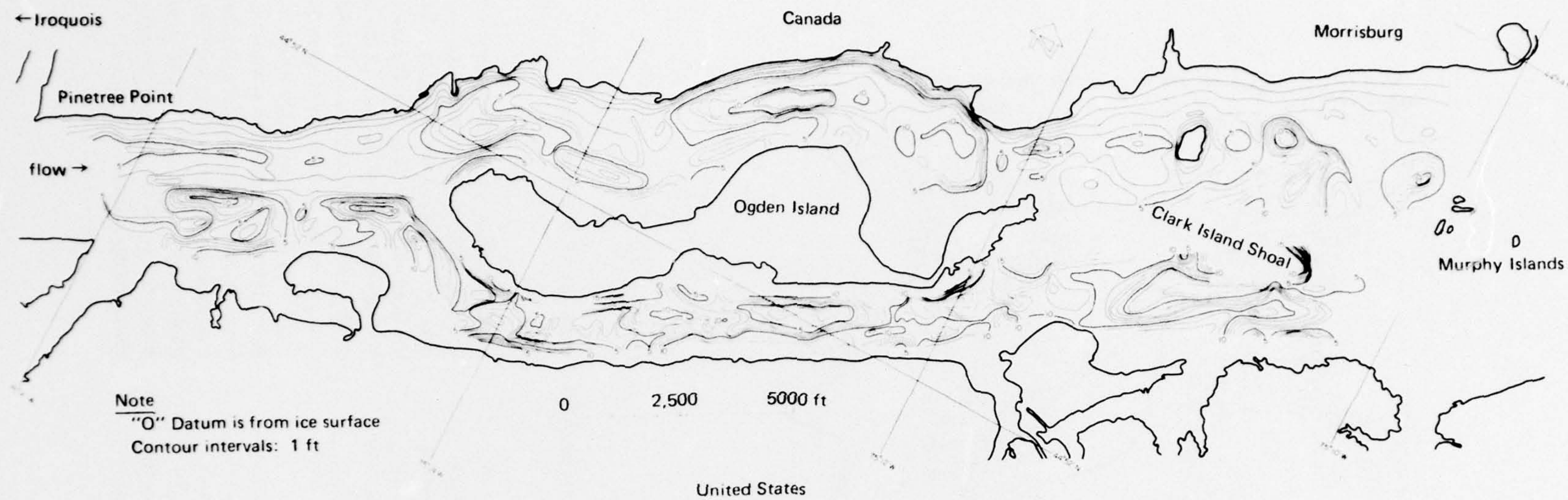

Figure 9. Frazil ice thickness in the Ogden Island area of the Saint Lawrence River – February 1976.

RESULTS

The finished contour map of the study area (Fig. 9) is drawn in contour intervals of 1 ft and includes an average 12 to 20 in. of sheet ice. The lack of contours in areas reflects portions of strip charts which were not interpretable and areas where no flight lines existed. Factors contributing to frazil and brash ice accumulation about Ogden Island may be observed with the map. For instance, the restriction at the lower (eastern) end of the north channel clearly initiates the accumulation beneath the ice cover. Further, the subsurface Clark Island Shoal initiates the accumulation in the south channel. This is information which should influence future considerations in channel modification.

From the flight patterns described previously it can be seen that some areas, such as that directly below Ogden Island, were missed because the flight paths were too far apart. Longitudinal flight paths normally produced interpretable data, but transverse flight paths did not produce such data. No firm explanation for this may be given other than possible misadjustment of the graphic recorder and control unit when the final strip charts were made for the transverse flights. Changing the printing density was often necessary to bring out interfaces when signal strength was weak.

Aircraft control and stability were adequate for data acquisition at flight speeds of 40 to 60 knots. When collecting data at 40 knots using the procedure mentioned previously, vertical deviation was no more than 1.3 m, averaging about 0.6 m. The pilot, two personnel in the aircraft and one assistant on the bank were sufficient to perform the airborne data collection operation when the benchmarks were available. Lines of flight in a channel were flown in one direction so that consistent flight speed and location accuracy could be maintained.

Benchmarks which were flat on the ice could not be seen from the air; three colors were tried and all lost. This was especially true when ice had accumulated to form the cover, as was the case in the channels about Ogden Island. Landmarks, therefore, were used as benchmarks for this project.

Airboat operation in this area was unsatisfactory. Because of the ridges on the accumulated ice cover, the velocity and attitude of the antenna-transceiver unit could not be controlled. This gave unreliable data in position and in ice thickness. In areas where the surface was smooth or only slightly rolling, adequate data were obtained. It was found that the radar set and the recorder required insulation and heating when operated at temperatures below 0°C.

Data collected on the surface by manual operation of the utility antenna could be interpreted much more easily than those obtained from the air using the same equipment. This can be seen in Figures 10 and 11, which are strip charts showing a surface profile and an aerial profile of the same survey line. Air operation introduces reflection noise into the data; likewise, more energy is coupled into the ice when the antenna is in physical contact with the surface.

Table I lists the manual soundings, also made along this line, for both the pole depth technique and the plate depth technique. Note that the thicknesses by plate measurement were consistently smaller than those by the pole measurement. The particle bonds within the frazil were quite degenerated near the bottom in this area, so that the plate appeared to compact and/or dislodge some of the frazil before the mass could be felt. Since the river current was strong beneath the ice, the flow differential at the frazil/ice interface set up distinct vibrations in the pole as it extended beyond the frazil mass. Therefore, the pole technique appeared to give the better measurement.

Although strong returns and minimum noise were received while detecting frazil thickness in surface operation, a low signal to noise ratio was observed in airborne operations using the utility antenna. The weather and ice conditions contributed to make poor conditions for coupling the energy from the antenna-transceiver unit into the ice. Since precipitation during the survey period varied between rain and wet snow, the ice surface was often puddled with water. The bottom 2 ft of the frazil was degenerated and exhibited an electromagnetically degraded frazil/water interface. The antenna was, as mentioned, not designed for aerial operation.

Reflections and noise were so strong with aerial profiling that no adequate data evaluation could be made from the strip chart on site. Only after signal averaging on the computer and tuning the density of the strip chart was the ice thickness consistently interpretable. It is estimated that about 50% of the data were actually recovered from the strip chart. After darkening the interfaces that could be seen, one could interpolate these interfaces into the frazil/water boundary. An example of this can be seen in Figure 12. The dark wavy lines at the top of the strip chart are the air/ice and ice/water interfaces as recorded during airborne data collection. The waviness comes from fluctuations in altitude of the aircraft, not from surface relief. The vertical distance below the dark wavy line represents about 5 m of frazil. The horizontal distance between the vertical line below the marker pen and the vertical line immediately to its

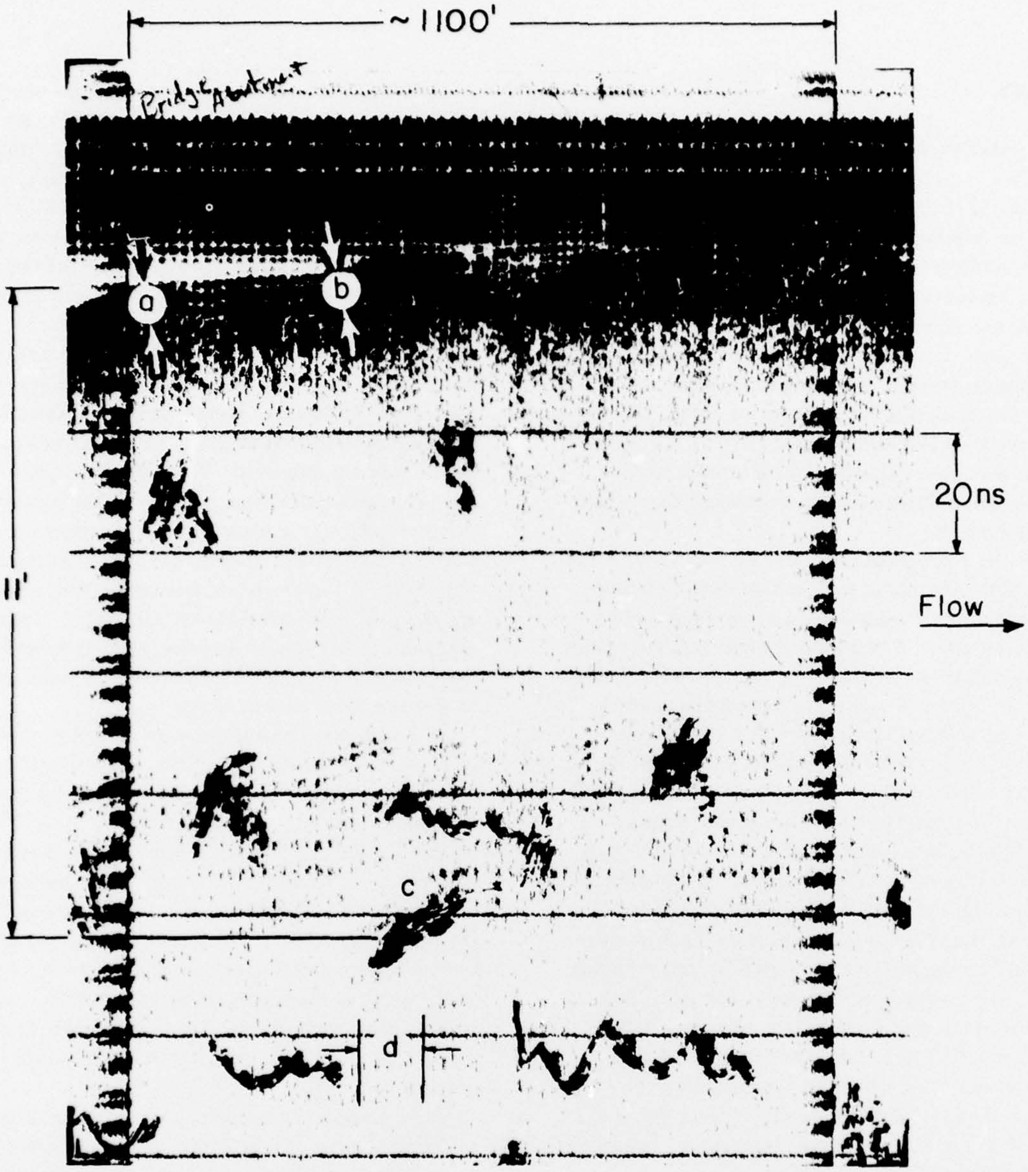

Figure 10. Airborne profile of a test section: a. Approximately 2 ft of sheet ice; b. Surface ice; c. Frazil/water interface; d. Test section.

right is about 400 m. Since in this study the thickness of the frazil beneath the surface was being measured, the resolution in the vertical scale is not such that one can accurately measure the sheet ice thickness. These interfaces, then, appear together. The frazil/water interface has been accentuated on this chart for ease of interpretation. The vertical lines are the benchmarks mentioned earlier. The inverted V's within the frazil are radar "hits" on an ice sheet that was underturned during the formation of this ice mass.

Ground truth data verified this characteristic.

The error in the aerial data in comparison with spot checks by sounding during the survey period is between 7% and 15%; this, however, may be due to positional error. Variations as high as 400% exist in comparison with ground data taken two weeks on either side of the survey period (refer to App. A and Table II). Figure 13, however, shows that the head between Iroquois and Morrisburg changed from 3.5 ft to 2.0 ft during the

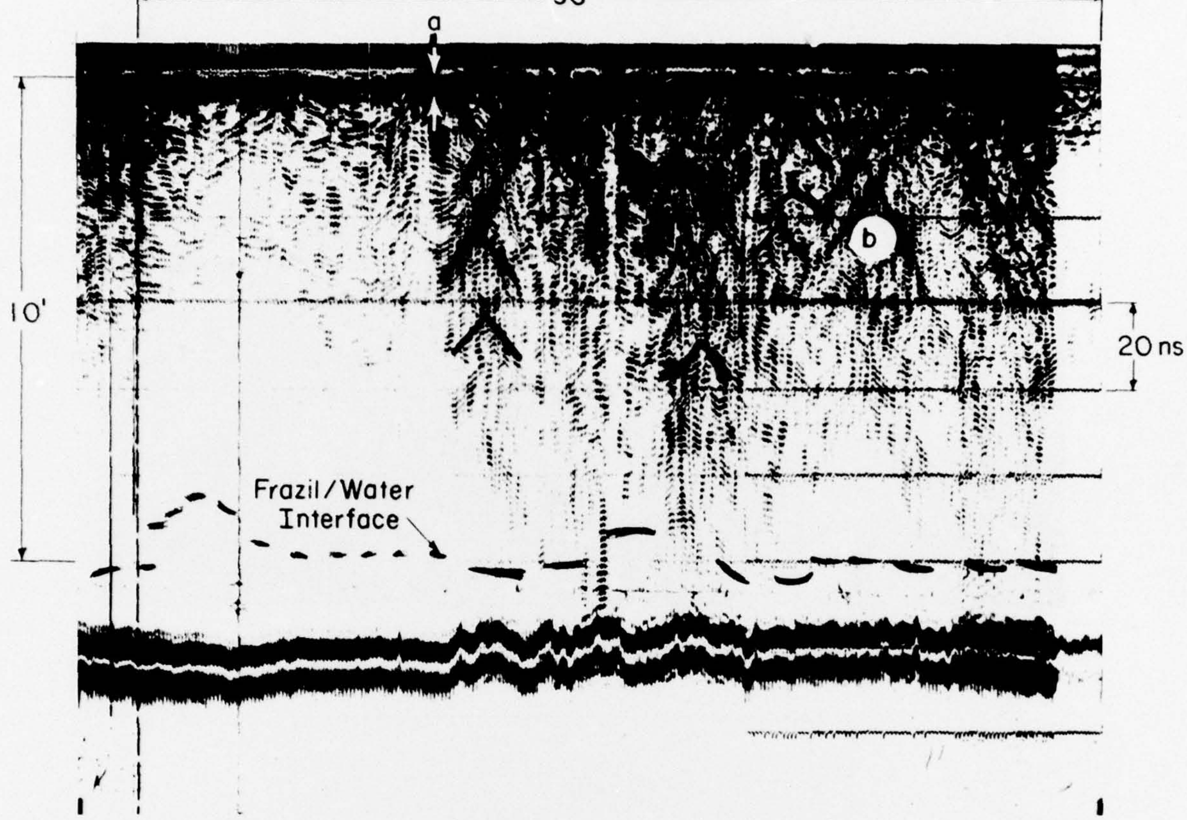

Figure 11. Surface radar profile of a test section: a. Surface ice (approx. 5 ns = 15 in. thick). b. Sheet ice targets within frazil.

month of February. Even more significantly, flow increased from 250,000 to 280,000 ft^3/s during the same period. This indicates that the frazil was being reduced by the warming water and increased flow. Such a variation in frazil thickness under those circumstances is not surprising.

The position accuracy was quite poor because of inadequate benchmarks. Overall, transverse accuracy is estimated to be ± 25 m and longitudinal accuracy ± 50 m.

Ground data and aerial data are compared in Appendix A. The ground data were obtained by the St. Lawrence Seaway Development Corporation and Ontario Hydro with the two sounding techniques previously mentioned.

CONCLUSIONS

The radar profiler manufactured by Geophysical Survey Systems, Inc. appears to be adequate for the detection of frazil and brash ice in fresh water.

The remote sensing and data reduction technique developed for this project can provide sufficient data to produce a contour map of ice thickness. The resolution of such contours is a function of the range selection. Resolution of 2% of full-scale was interpretable in this work.

The use of antennae designed for surface profiling is not recommended. Use of surface antennae, such as the utility antenna, introduces severe reflections and noise into the data. An antenna-transceiver

Figure 12. Interpretation of the graphic recorder charts.

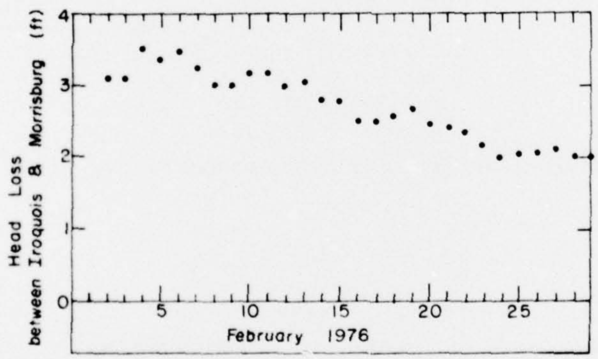

Figure 13. Daily head loss on the Saint Lawrence River between Iroquois Dam and Morrisburg for the month of February 1976.

specifically designed for aerial data collection should be used.

With the contour map generated for the study area (see Fig. 9) the accumulation pattern of the frazil and brash ice could be analyzed.

RECOMMENDATIONS

This project has established a capability and developed a technique for the remote sensing of frazil and brash ice accumulation. These accomplishments should be applied toward further investigations in the Ogden Island area of the Saint Lawrence River. The following procedures are recommended:

1. Periodic ice thickness contours should be obtained to evaluate the effects of significant events such as a freeze-up, a strong cold period, a strong warm period, or a noticeable change in the head loss between Iroquois and Morrisburg. Such data would exhibit the movement of ice within the study area as well as movement into and out of the area. The correlation of available

data such as water temperatures, air temperatures, solar radiation area of open water, and flow will further describe the thermal regime of the area. The theoretical volume of brash and frazil ice generated can then be compared with the volume attached beneath the river ice cover.

2. Detailed descriptions on the ice cover growth in the area must be coupled with ice thickness measurements as soon as possible (airboat or helicopter) to determine the origin of the ice in the channels, i.e. to determine whether deposition occurs mainly during initial growth of the sheet or consistently throughout the season. This basic question must be answered before any remedial action can be attempted.

3. Ground truth data should be taken periodically in specified areas of interest to supplement aerial data. Members of the data collection team should decide upon a common technique and periodically compare their results to assure consistent data.

4. Registration lines should be made by benchmarks on the ice surface rather than by the alignment of features on the shore. These surveyed benchmarks must be three-dimensional and at least 1 m square × 1.5 m high. Flat benchmarks cannot be located accurately from the air. At least two three-dimensional benchmarks are needed along each registration line where a longitudinal line of flight will cross. For the sake of economy, benchmarks should be in place prior to the survey team coming on site. The pilot should fly toward a fixed point in periods of good visibility. Otherwise, a particular azimuth should be followed. This facilitates the transfer of such a flight line to the map.

5. The use of antennae designed for surface profiling is not recommended. Use of surface antennae, such as the utility antenna, introduce severe reflections and noise into the data. An antenna-transceiver specifically designed for aerial data collection should be used. This will allow the antenna-transceiver to be mounted between the skids of the helicopter or slung below it. The antenna should be designed to operate at a particular distance above the surface, i.e. the directivity should be such that excessive integration (coverage by the irradiated beam pattern) of the area below the antenna is eliminated. The time of travel through the depths of frazil encountered is considered long for the electronics of the system. Thus, it is necessary either to maximize the amount of energy penetrating the ice or to increase the sensitivity of the receiver in order to have a strong interface reflection. Better antenna design will help.

6. A ground crew is required for on-site data evaluation. A faster transfer of data to graphic form is needed. This can be done by obtaining a faster graphic recorder, – a recorder which can run at close to the same speed at which the data were taken. Further, a storage oscilloscope could give the system a quick-look capability for signal intensity and interface (frazil/water) location. If significant noise is still in the airborne system with a new antenna-transceiver unit, the radar unit needs to incorporate some sort of noise reduction scheme. At least this should include the signal averaging now implemented by computer.

7. Flight patterns need to be designed to coincide more nearly with suspected accumulation areas. This will facilitate the contour mapping and increase its accuracy. *This does not imply that the flight pattern* should be less dense in places. Rather, it requires that areas of extreme relief have additional flight lines.

8. The transverse flight data collection technique should be analyzed and varied to determine what approach is required to obtain interpretable data. Flight line approach and speed and antenna height above the surface of the ice should be varied. Transverse data are not necessary, but provide complementary data to the longitudinal data.

9. It is theorized that each type of interface has its own characteristic signature in the returning signal, an assumption based on work done in seismology. To investigate this, digital filtering can be used to enhance the data reduction so as to enhance signatures based on frequency characteristics. The technique aids in cleaning up the data by ignoring the spurious signals occurring outside the frequency window associated with the interface of interest. Data reduction and interpretation in the system have need for improvement, and implementation of these techniques would greatly facilitate this data manipulation.

10. Flow data from critical and characteristic locations should be obtained concurrently with contour data. Entrainment and deposition thresholds can then be approximated when correlated with environmental data. *Entrainment and deposition threshold data will* provide guidance in decisions concerning actions required to minimize ice accumulation in any location. Flow sensors should be used which are insensitive to the type of clogging encountered with frazil and slush (this will probably require an electromagnetic current meter). So little is known about the interaction between the flow regime and the frazil deposition and entrainment thresholds that detailed velocity profiles should be obtained. The flow profile in close proximity to the interface should be of main interest.

11. Engineering data are required on the structure and strength characteristics of the frazil and brash ice in the study area. These data would include density, porosity, permeability, shear strength and Rammsonde testing. Electromagnetic conductivity should be checked within the study area to determine the variation. This variation affects the calibration of the radar profiler. It follows that these data then need to be related to navigation impediment and head losses.

12. In certain areas the frazil/ice interface exhibited a waveform having a reasonably constant characteristic frequency. Investigation into this phenomenon would provide insight into the character of the deposition and entrainment thresholds. Data for such an investigation would be obtained during normal contour operations by increasing the flight line density in the area of interest. A description of the flow regime would also be required along the direction of the waveform.

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APPENDIX A. COMPARISON OF GROUND AND AERIAL DATA

The object of this section is to provide a means of comparison between the ground data and the aerial data. There are two factors affecting the comparison of these data. The first, a positional error associated with the location of the ground data, is due to the lack of precision in locating the points at which manual soundings were made. The second factor concerns the assumed change in the ice thickness which occurred between the times when ground and aerial data were taken. The flow and head variations during the month of February (discussed in *Results and Conclusions*) support this assumption.

The author feels that a comparison between the data taken from the air and from the ground is almost like comparing data from different study areas. Because the flow was so variable between the time that ground and aerial data were taken, neither set of data can prove or disprove the other set. The author felt compelled to present both sets of data, however, so that the general order of agreement could be observed.

The error due to positional inaccuracy is depicted in Figure A1, where a typical portion of the contour map in the south channel is shown. Ground data points are estimated to be at the center of each circle, which has an arbitrary radius of 100 ft. The soundings at these points are in the inset table. The aerial data are represented by the contours in the channel. Out of the 10 points, 7 circles can enclose the exact sounded depth, 2 circles are 20% higher than the highest contour enclosed, and 1 circle encloses a contour which is four times larger than the sounded depths. The error source associated with the last three circles mentioned is probably not positional. It is assumed that it is due to the changes in the ice thickness between the aerial and ground data collection periods. (From this sample, it appears that a majority of the error may be positional.)

Table A1 lists the radar and ground measurements which are graphed in Figure A2. These data were taken by three different field parties of the organizations indicated, using two techniques. The techniques are

Line	Date	Circle a	Circle b	Circle c
5	7-8 Feb	-	8.7'	4.75'
6	7-8 Feb	4.8'	4.5'	4.8'
7	7-8 Feb	-	6.75'	1.6'
7A	12-13 Feb	5.5'	7.0'	7.3'

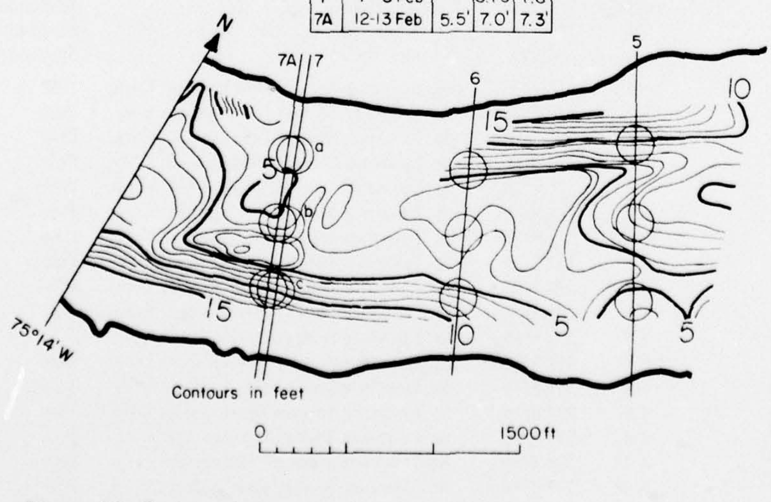

Figure A1. Positional error associated with the location of ground data.

Table AI. Frazil ice thickness data (see text).

Remote measurement by radar, 2/20-21/76 (ft)	*Depth (ft)*	*Manual measurement*		
		Date	*Organization*	*Technique*
6.1	6.4	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
2.3	7.3	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
3.9	4.0	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
5.5	8.5	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
7.0	7.1	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
7.3	9.5	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
5.4	7.8	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
9.8	8.6	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
3.0	7.8	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
8.1	8.1	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
9.8	1.5	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
7.1	6.3	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
9.8	6.5	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
9.5	9.1	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
5.7	5.8	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
4.1	4.75	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
2.9	1.67	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
9.7	7.3	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
4.6	7.0	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
6.0	5.5	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
5.4	4.9	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
3.0	8.9	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
4.2	5.75	2/12-13/76	St. Lawrence Seaway Development Corp.	Pole
12.75	9.5	2/10/76	Ontario-Hydro	Suspended plate
10.5	11	2/10/76	Ontario-Hydro	Suspended plate
11	12	2/10/76	Ontario-Hydro	Suspended plate
9.75	11.5	2/10/76	Ontario-Hydro	Suspended plate
10	14	2/10/76	Ontario-Hydro	Suspended plate
11.5	14.75	2/10/76	Ontario-Hydro	Suspended plate
11.5	12	2/10/76	Ontario-Hydro	Suspended plate
4.33	6.67	2/11/76	Ontario-Hydro	Suspended plate
3.5	3.1	2/11/76	Ontario-Hydro	Suspended plate
6.5	13.5	2/11/76	Ontario-Hydro	Suspended plate
8.5	13.1	2/11/76	Ontario-Hydro	Suspended plate
10.5	19	2/11/76	Ontario-Hydro	Suspended plate
9.5	16	2/11/76	Ontario-Hydro	Suspended plate
10.25	10.5	2/11/76	Ontario-Hydro	Suspended plate
9.25	7.5	2/11/76	Ontario-Hydro	Suspended plate
10.5	15	2/11/76	Ontario-Hydro	Suspended plate
3.25	1.5	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
4.0	2.0	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
5.5	5.6	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
5.8	5.8	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
7.1	7.1	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
9.5	6.9	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
6.5	7.3	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
7.5	7.6	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
10	4.2	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
7.8	4.7	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
10	4.5	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
8	8.7	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
6.7	4.8	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
3.1	4.5	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
5.8	4.8	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
4.50	4.75	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
5.8	6.75	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole
9	1.6	2/7-8/76	St. Lawrence Seaway Development Corp.	Pole

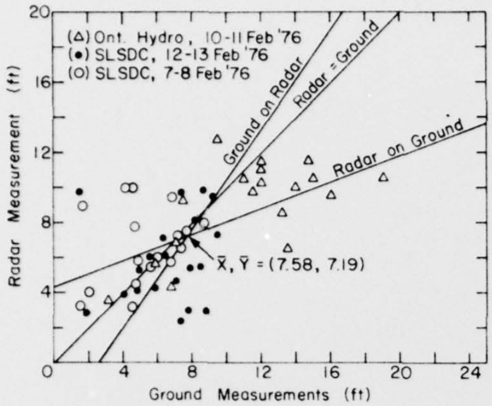

Figure A2. Comparison of radar measurements and ground measurements.

described in the *Approach* section. Figure A2 considers the error from the assumed change in the ice thickness that occurred between the times that ground and aerial data were taken, and displays a regression analysis of the data.

A radar-ground line of perfect agreement was placed in Figure A2 for reference. The radar on ground line, the least squares line assuming the ground data to be the independent variable, has the equation:

$$R = 4.46 + 0.36G$$

where R is radar measurement and G ground measurement.

The ground on radar line, the least squares line assuming the radar data to be the independent variable, has the equation:

$$G = 2.54 + 0.70R.$$

It is tempting to assume that the ground data are "ground truth" data; however, the positional error and the error associated with the use of two different measurement techniques will not allow this.

Two regression lines can be used to evaluate the applicability of a first-order curve. The deviation of the two lines indicates that the data do not readily fit a linear relationship. If the error in the data itself were less, one would attempt to find a higher-order fit.

The standard error of estimate for ground measurements as the independent variable is

$$S_{R,G} = \left[\frac{\Sigma R^2 - a_0\,\Sigma R - a_1\,\Sigma GR}{N}\right]^{1/2}$$

$$= 2.34 \text{ ft}$$

where $N = 57$, a_0 and a_1 are the coefficients of the first order regression line given by

$$a_0 = \frac{\Sigma R\,\Sigma G^2 - \Sigma G\,\Sigma GR}{N\,\Sigma G^2 - (\Sigma G)^2}$$

$$= 4.46$$

and

$$a_1 = \frac{N\,\Sigma GR - \Sigma G\,\Sigma R}{N\,\Sigma G^2 - (\Sigma G)^2}$$

$$= 0.36.$$

The standard error of estimate for aerial measurements as the independent variable is

$$S_{G,R} = \left[\frac{\Sigma G^2 - b_0\,\Sigma G - b_1\,\Sigma RG}{N}\right]^{1/2}$$

$$= 3.28 \text{ ft}$$

where $b_0 = 2.54$ and $b_1 = 0.70$ (b_0 and b_1 are found from the corresponding a_0 and a_1 equations when the variables are reversed).

A deviation twice the standard error of estimate will include about 95% of the data. In the case where the ground data are independent, this means that 95% of the radar data fall within a 4.7-ft deviation. Likewise, when aerial data are considered to be independent, 95% of the ground data falls within a 6.6-ft deviation.

The coefficient of correlation for the data is

$$r = \frac{N\Sigma RG - \Sigma G\,\Sigma R}{\left\{[N\Sigma G^2 - (\Sigma G)^2]\,[N\Sigma R^2 - (\Sigma R)^2]\right\}^{1/2}}$$

$$= 0.50$$

regardless of which variable is considered to be independent.